

Neutrino Factory Superbeam

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Abstract

We discuss the optimization of a neutrino factory for large $\sin^2 2\theta_{13}$, where we assume minimum effort on the accelerator side. This implies that we use low muon energies for the price of an optimized detection system. We demonstrate that such a neutrino factory performs excellent if combined with the electron neutrino appearance channel. Instead of the platinum channel operated with the muon neutrinos from the muon decays, we propose to use the initial superbeam from the decaying pions and kaons, which might be utilized at little extra effort. Since we assume out-of-phase bunches arriving at the same detector, we do not require electron charge identification. In addition, we can choose the proton energy such that we obtain a synergistic spectrum peaking at lower energies. We find that both the superbeam and the neutrino factory beam should be used at the identical baseline to reduce matter density uncertainties, possibly with the same detector. This effectively makes the configuration a single experiment, which we call “neutrino factory superbeam”. We demonstrate that this experiment outperforms a low-energy neutrino factory or a wide band beam alone beyond a simple addition of statistics.

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1. Introduction

Future neutrino oscillation facilities are primarily targeted towards the discovery of a non-zero $\sin^2 2\theta_{13}$, the neutrino mass hierarchy determination, and the measurement of leptonic CP violation. All of these measurements depend heavily on the magnitude of $\sin^2 2\theta_{13}$. Two examples for experiments under way, which will test the magnitude of $\sin^2 2\theta_{13}$, are the T2K superbeam (SB) project [1] and the Double Chooz reactor experiment [2]. From all such neutrino oscillation experiments, one may expect a $\sin^2 2\theta_{13}$ sensitivity limit of about 0.01 in a decade from now (see, *e.g.*, Ref. [3]), *i.e.*, $\sin^2 2\theta_{13}$ can either be constrained to be smaller than this value, or it will be discovered until then. Since the discovery of $\sin^2 2\theta_{13}$ affects the experimental strategy how to measure the mass hierarchy and CP violation, this “branching point” [4] will, at the latest, tell

us how to proceed.

If $\sin^2 2\theta_{13}$ turns out to be small, one may optimize for a maximum $\sin^2 2\theta_{13}$ reach of all measurements. It seems that a neutrino factory [5–8] (NF) or a higher gamma beta beam [9, 10] could be the most promising alternative; for the optimization discussions, see, *e.g.*, Refs. [11, 12]. For large $\sin^2 2\theta_{13}$, the measurement far away from the oscillation maximum and matter density uncertainties affect the NF performance [8, 13]. Therefore, other alternatives may outperform a NF, such as SB upgrades or beta beams (see, *e.g.*, Refs. [11, 14] for a direct comparison).

Recently, potential improvements in the muon charge identification (CID) at low energies (see, *e.g.*, Ref. [15]) have brought back a NF into the discussion for large $\sin^2 2\theta_{13}$. In Ref. [16], a muon energy of 4.12 GeV was proposed at baselines of 1 000 to 1 500 km, an option similar to a wide band beam in terms of neutrino energies and baseline. The relatively low muon energy allows for a significant reduction of the effort on

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the accelerator side, which means that this option might indeed be competitive to SB upgrades, *etc.* Other alternatives to improve the NF for large $\sin^2 2\theta_{13}$ are the use of the magic baseline [12, 17], or the platinum channel $\nu_\mu \rightarrow \nu_e$ (with the ν_μ 's coming from the muon decays), which requires electron detection with CID [12]. In this way, the impact of matter density uncertainties can be significantly reduced as well.

In this letter, we discuss the optimization of a low-energy NF. We compare such an optimized experiment to wide band beams and beta beams. Furthermore, we propose to use the neutrinos from the secondary pion/kaon beam in addition to the NF beam. This SB, possibly targeted towards the same detector, will provide similar information to the platinum channel. However, it has two major advantages: First, the (at least in a magnetized iron calorimeter) very difficult electron CID is not required if operated out-of-phase with the NF beam. Second, the proton energy can be chosen such that the event rates are peaking at lower energies, where the NF has less events. We discuss the requirements for such a hybrid configuration, which we call “neutrino factory superbeam” (NF-SB), and we show the physics potential.

2. Setup and Experimental Requirements

The primary information from a NF comes from the “golden” $\nu_e \rightarrow \nu_\mu$ appearance channel [7].³ The two major challenges for large $\sin^2 2\theta_{13}$ are the matter density uncertainties and the lack of events at low energies, where the interesting higher-order oscillation effects are present. As demonstrated in Ref. [12], complementary information from the T-conjugated $\nu_\mu \rightarrow \nu_e$ appearance channel (platinum channel) would help, partly because of the correlated matter effect. However, CID for electrons in a magnetized iron calorimeter appears to be difficult because the electrons produce showers early (though it may not be impossible for low neutrino energies). In this letter, we propose to use the SB from the pion and kaon decays instead of the platinum channel.

The schematics for such a setup can be found in Figure 1. We require that it be operated out-of-phase with the NF beam, which means that CID will not be required for this channel. In addition, the proton energy can be adjusted within the range acceptable for the NF⁴ such that a spectrum peaking at lower energies can be obtained. As one can see from Figure 1, there are two major requirements for such a setup: First, the geometry has to be chosen such that the tertiary and quaternary neutrino beams point towards the same detector (not to scale). Second, the target station has to be able to separate and focus the pion and kaon charges in a way that both experiments can be operated simultaneously. From Figure 1, this requirement may be acceptable if we only use half of the luminosity of an exclusive NF (because only one polarity can be operated at the same time). However, one may speculate that a more sophisticated target station might recycle a fraction of the muons from the SB mode. Note that, for the NF plus SB, we have now three phenomenological degrees of freedom: E_p , E_μ , and L .

The main prerequisite for a low-energy NF is an improved detection system with sufficient golden channel efficiencies at low energies. These efficiencies with a threshold possibly as low as 0.5 GeV might be obtained by cuts leading to a higher charge mis-identification background, or a more refined detector than a magnetized iron calorimeter (such as a NO ν A-like detector or a liquid argon detector with a large magnetic volume). For large $\sin^2 2\theta_{13}$, such a background will not be very important as long as the background level is $\lesssim \sin^2 2\theta_{13}$. We follow Refs. [12, 16] by using a low-threshold (500 MeV) with improved energy resolution option ($15\%/\sqrt{E}$), which we call **Golden***. We use 50% efficiency for the golden channel requiring CID, and 90% efficiency for the disappearance channel without CID. Note that an even higher appearance efficiency may be obtained for the price of larger backgrounds. We use a total luminosity of 5 yr running time $\times 10^{21}$ useful muon decays/year $\times 50$ kt detector mass in

³Note we will also use antineutrinos in all of the discussed channels.

⁴The acceptable range is relatively wide $8 \text{ GeV} \lesssim E_p \lesssim 30 \text{ GeV}$ (see, *e.g.*, Ref. [18]).

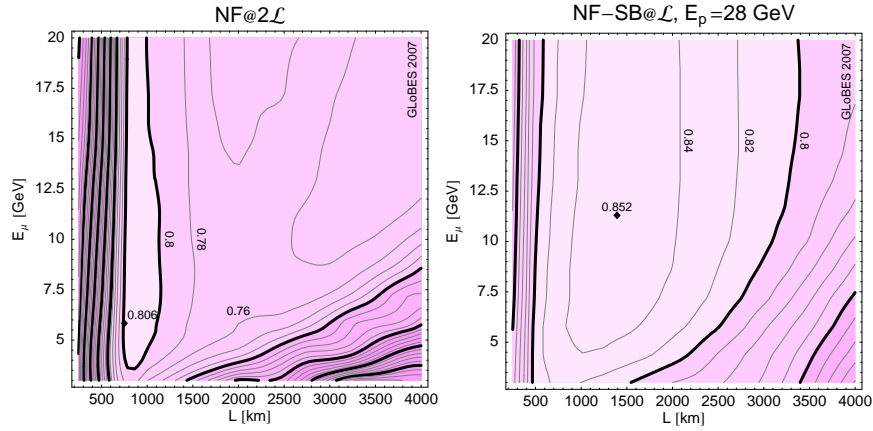


Figure 3. Fraction of δ_{CP} for which CP violation can be measured as a function of L and E_μ ($\sin^2 2\theta_{13} = 0.1$, 3σ confidence level). The left panel is for a NF alone with twice the luminosity as in the right panel. The right panel is for a NF plus SB combination with a fixed proton energy of $E_p = 28$ GeV. The contours are spaced by 0.02, where the thick curves correspond to a fraction of $\delta_{\text{CP}} \in \{0.8, 0.7, 0.6, \dots\}$. The optima are marked by the diamonds. The luminosity “ \mathcal{L} ” stands for $0.5 \cdot 10^{21}$ useful muon decays/yr.

(see, *e.g.*, Ref. [24]). In addition, we assume that Δm_{21}^2 , θ_{12} , and the matter density will be known at the level of 5%.

3. Optimization for Large $\sin^2 2\theta_{13}$

As far as the optimizations of a low-energy NF and the NF-SB are concerned, let us first of all focus on the NF alone. In Figure 3, left panel, we show the fraction of (true) δ_{CP} for which CP violation can be measured as a function of L and E_μ (for $\sin^2 2\theta_{13} = 0.1$). At the optimum (diamond), one can establish CP violation for 81% of all possible values of δ_{CP} . One has close-to-optimum performance for $L \sim 800 \text{ km} - 1300 \text{ km}$ and $E_\mu \gtrsim 4 \text{ GeV}$, which is consistent with the configuration discussed in Ref. [16]. For the mass hierarchy, we find that $L \gtrsim 800 \text{ km}$ to establish the mass hierarchy for any δ_{CP} (the E_μ -dependence is moderate). In addition, note that for such a large $\sin^2 2\theta_{13}$, none of the discussed facilities has a problem to establish a non-zero $\sin^2 2\theta_{13}$.

In Figure 3, right panel, we show the same optimization for NF-SB with a fixed proton energy of $E_p = 28 \text{ GeV}$ and half the useful number of

muon decays from the last example. At the optimum (diamond), one can establish CP violation for 85% of all possible values of δ_{CP} . The optimal baseline range depends on E_μ . For instance, one has close-to-optimum performance for $L \sim 800 \text{ km} - 1500 \text{ km}$ for $E_\mu \gtrsim 4 \text{ GeV}$. For the mass hierarchy, shorter baselines $L \gtrsim 500 \text{ km}$ are, in principle, sufficient. This effect has been discussed in Ref. [25]. Since the NF luminosity in this hybrid is only half of the one for the NF alone, we conclude that we have a identified a synergy between the NF and the SB which goes beyond the simple addition of statistics (for a definition of synergy, see Ref. [26]). Note that the SB alone operated at double luminosity approximately compares to the low-energy NF alone (for $\sin^2 2\theta_{13} = 0.1$ and the same detector).

Now one may argue that it may be better to use a combination with two different baselines in the fashion of Ref. [27] (NF plus SB). Therefore, we show in Figure 4 the two-baseline optimization of the NF and SB with uncorrelated matter effect and a fixed muon energy of $E_\mu = 5 \text{ GeV}$. The optimum turns out to be close to the same-baseline diagonal. However, it is somewhat worse than for the correlated matter density case above.

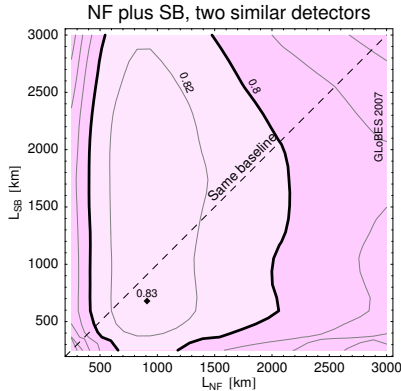


Figure 4. Two-baseline optimization of the NF plus SB with uncorrelated matter effect: Fraction of δ_{CP} for which CP violation can be discovered as a function of L_{NF} and L_{SB} (3σ). The muon energy is $E_\mu = 5$ GeV, and $\sin^2 2\theta_{13} = 0.1$.

Since a option requiring only one site and, possibly, only one detector is much more cost efficient, we will not discuss the two-baseline case anymore. We have, in addition, tested a 500 kt water Cherenkov detector for the SB part together with the 50 kt *Golden**. More or less, we obtain the same qualitative results with the difference of a much higher fraction of δ_{CP} : CP violation can be measured for about 91% of all values of δ_{CP} (for $\sin^2 2\theta_{13} = 0.1$). Of course, this option would require an additional very large detector. Furthermore, we have checked that our optimization results to not change for somewhat smaller $\sin^2 2\theta_{13} = 0.05$. In the following section, we will use these standard setups from the optimization discussion above as given in Table 1.

4. Comparison of Facilities

We compare in Figure 5 the different setups from Table 1 for different values of (large) $\sin^2 2\theta_{13}$. Obviously, the NF-SB outperforms any of the chosen facilities for large enough $\sin^2 2\theta_{13}$ except for the beta beam. In particular, it is significantly better than low-E NF (with or without platinum channel), and slightly better than High-E NF_{2B} (except for $\sin^2 2\theta_{13} = 0.01$). Note that

these setups are operated at the double muon decay rate compared to the NF-SB, which means that the information from NF and SB is very complementary in terms of channel and spectrum. As far as the beta beam is concerned, we find that it has the best absolute performance. However, given the relatively high gamma and the challenging ion decay rates, it is difficult to judge how this setup compares in terms of feasibility and effort. The comparison to the wide band beam (in this case with a 500 kt water Cherenkov detector compared to the 50 kt *Golden** used for the NF-SB hybrid) depends very much on $\sin^2 2\theta_{13}$: For very large $\sin^2 2\theta_{13} \simeq 0.1$, the wide band beam might be the natural choice, because it is based on known technology. However, for a somewhat smaller $\sin^2 2\theta_{13}$, the NF-SB is significantly better.

We have also studied further potential improvements of the NF-SB. Very little physics reach can be gained by the additional use of the magic baseline or platinum channel, or by better knowledge on the matter density profile, since the underlying correlations are already resolved. The most significant improvement can be obtained by luminosity upgrades, such as by using a large water Cherenkov detector (for the SB) in addition to *Golden** at the same site. In this case, even the beta beam can be outperformed for very large $\sin^2 2\theta_{13}$. Note that one could imagine different staged scenarios with this observation, such as WBB_{*Golden**} followed by NF-SB. We expect that further significant improvements could be obtained by better absolute efficiencies for the muon neutrino appearance channel (for the price of larger backgrounds), by recycling a fraction of the muons produced in the SB channel for the NF, or by a further optimization of proton energy and horn characterizing the SB.

5. Summary and Discussion

We have studied a low-energy neutrino factory (NF) in combination with a superbeam (SB) produced in the decay chain of the same protons, which we have called “neutrino factory superbeam”. We have demonstrated that this configuration outperforms a low-energy NF alone be-

Setup name	Description/Parameters	Det.	m_{Det}	Ref.
WBB _{WC}	$E_p = 28 \text{ GeV}$, $P_{\text{target}} = 4 \text{ MW}$	WC	500 kt	[20]
Low-E NF	$E_\mu = 5 \text{ GeV}$, $L = 900 \text{ km}$, 10^{21} umd	Golden*	50 kt	this
Low-E NF&Pt	Same as Low-E NF, plus platinum channel	Golden*	50 kt	this
High-E NF _{2B}	$E_\mu = 20 \text{ GeV}$, $L = 4\,000 \text{ km} + 7\,500 \text{ km}$, 10^{21} umd	Golden*	2 x 50 kt	[12]
NF-SB	$E_\mu = 5 \text{ GeV}$, $L = 1\,250 \text{ km}$, $0.5 \cdot 10^{21} \text{ umd}$, $E_p = 28 \text{ GeV}$, $P_{\text{target}} = 4 \text{ MW}$ (SB)	Golden*	50 kt	this
BB350	$\gamma = 350$, $L = 730 \text{ km}$, $5.8 \cdot 10^{18} \text{ useful } ^6\text{He}$ decays/yr, $2.2 \cdot 10^{18} \text{ useful } ^{18}\text{Ne}$ decays/yr	WC	500 kt	[10]

Table 1

Setups used for the comparison. The running time is five years for each polarity for all setups. The abbreviation “umd” stands for “useful muon decays per year”, the abbreviation “WC” for a water Cherenkov detector, and the label **Golden*** for our optimized detector (see description in Section 2 and Ref. [12]).

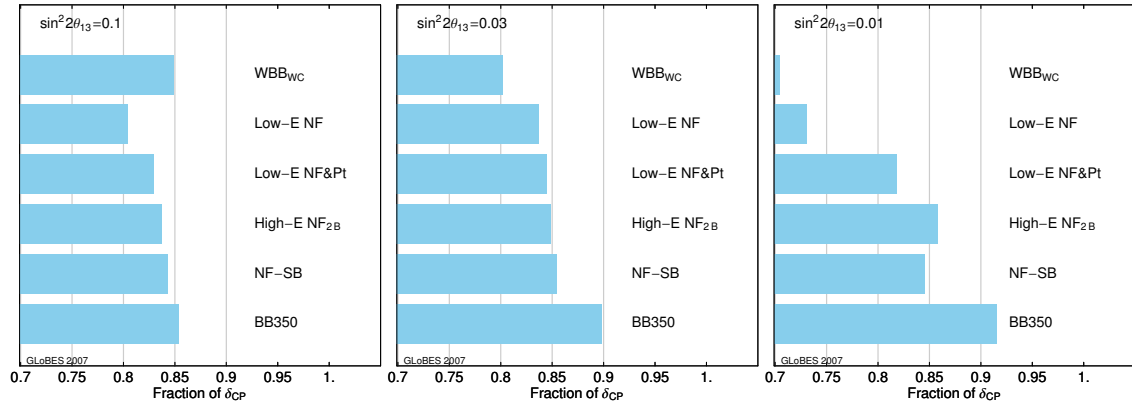


Figure 5. Comparison of the fraction of (true) δ_{CP} for which CP violation can be discovered (3σ) for the different facilities listed in Table 1. The different panels correspond to different values of $\sin^2 2\theta_{13}$, as given in the captions.

yond a simple addition of statistics even if one can use the platinum channel, as well as it outperforms a wide band beam with the same proton energy. The reason for this excellent performance is the SB spectrum peaking at lower energies, and the information from the T-conjugated $\nu_\mu \rightarrow \nu_e$ channel at the same baseline (*i.e.*, with correlated matter effect).

As far as the technical requirements for such a configuration are concerned, the same detector might be used at the same baseline. As for any low-energy neutrino factory, sufficiently good efficiencies at low energies are required. The extra

effort mainly reduces to a more sophisticated target station, which has to separate the pion and kaon charges and utilize them for the NF and SB. In addition, we have assumed that the NF and SB bunches arrive out-of-phase at the (possibly same) detector. For the electron neutrino detection, we have required a relatively high efficiency without CID, which is different from the platinum channel (where the requirement of CID significantly reduces the efficiency). As far as systematics is concerned, we expect this experiment to be of low risk: The NF systematics has been assumed very conservatively, and the wide band

beam is rather robust with respect to systematics [14]. This might be an important decision criterion in comparison to narrow band beams.

From the optimization, we have found $L \sim 800 \text{ km} - 1500 \text{ km}$ and $E_\mu \gtrsim 4 \text{ GeV}$ to be close-to-optional, which, for instance, corresponds to Fermilab to Homestake or Henderson. For the proton energy, we have tested two configurations at the lower end upper end of the admissible range for a NF, and we have chosen $E_p = 28 \text{ GeV}$. This means that we obtain a completely different configuration from a high-energy NF optimized for small $\sin^2 2\theta_{13}$ [12] in terms of baselines, muon energy, and target station. For the detector, the need for high efficiencies at low energies is independent of the NF configuration (but not a prerequisite for a high-energy NF). However, higher backgrounds may be admissible for the low-energy NF, which means that the overall efficiency could be higher. Although a high-energy NF with two baselines (and possibly platinum channel) might be used for large $\sin^2 2\theta_{13}$ as well, the effort might be considerably higher. The same, in principle, applies to a higher gamma beta beam. We conclude that a reasonable decision can be made when the branching point sensitivity $\sin^2 2\theta_{13} \simeq 0.01$ is reached. Before that point, one may want to develop two different NF approaches: One optimized for $\sin^2 2\theta_{13}$ reach operated as a discovery machine, the other optimized for large $\sin^2 2\theta_{13}$ operated as a precision instrument.

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